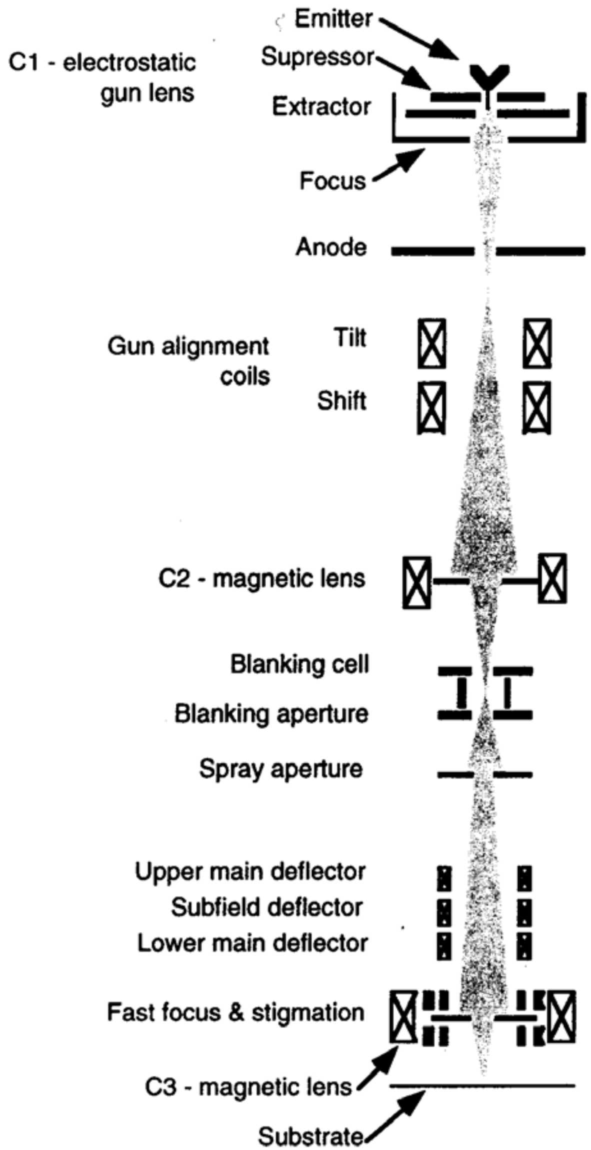
E298A/EE290B – Electron Optics Basics

- Sources
- Lenses
- Deflectors
- Blankers
- Resolution
    - Spherical, Chromatic, and Diffraction
- VB6 Electron Optics Layout
- Project Proposal

Electron Optical Layout for the Leica VB6



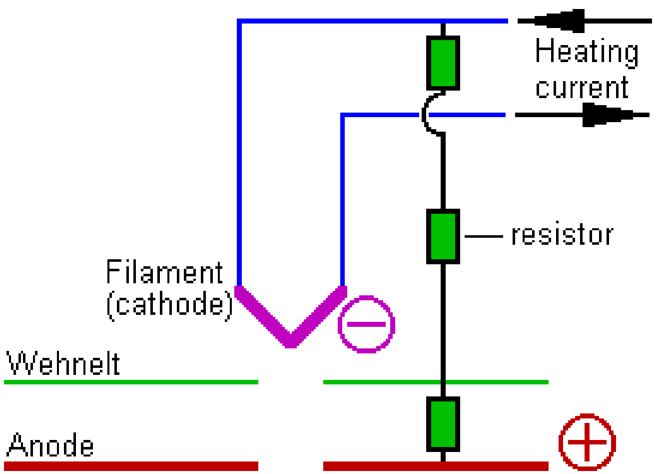
Source

- Tungsten
- LaB_6
- Thermal Field Emmiter (Schottky)
- Cold Field Emmiter

Electron emission, Is (amps/cm2), as a function of the absolute temperature, T, of a

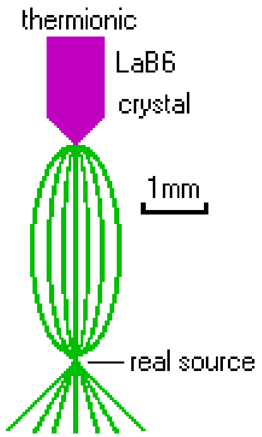
thermionic emitter is given by Richardson's equation:

$$I_s = AT^2 e^{-(B/T)}$$

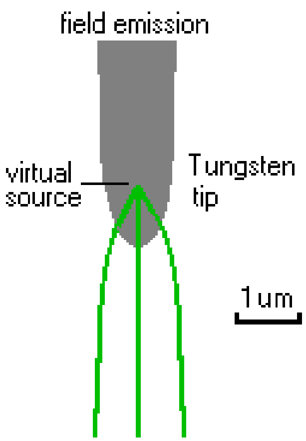


where A and B are constants that are determined empirically

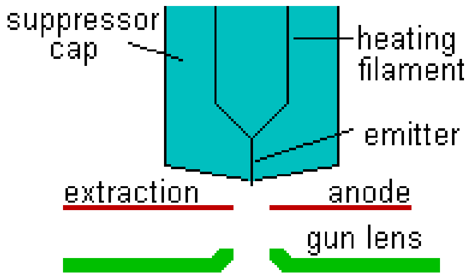
Electron Optics Basics – Sources LaB6



Electron Optics Basics – Sources FE



Electron Optics Basics – Sources TFE



Source Characteristics

Source Type	Brightness [amp/cm2/str]	Source Size	Energy Spread	Vacuum Required (Torr)
Tungeston	10^5	25um	2-3eV	10^{-6}
LaB_6	10^6	10um	2-3eV	10^{-8}
TFE	10^8	25nm	0.9eV	10^{-9}
Cold FE	10^9	5nm	0.22eV	10^{-10}

Electron Optics Basics - Brightness

$\beta = J/\Omega$ [amps/cm2/str]

Where J is the current density [amps/cm2]

And Ω is the solid angle

For a "spherical tip source"

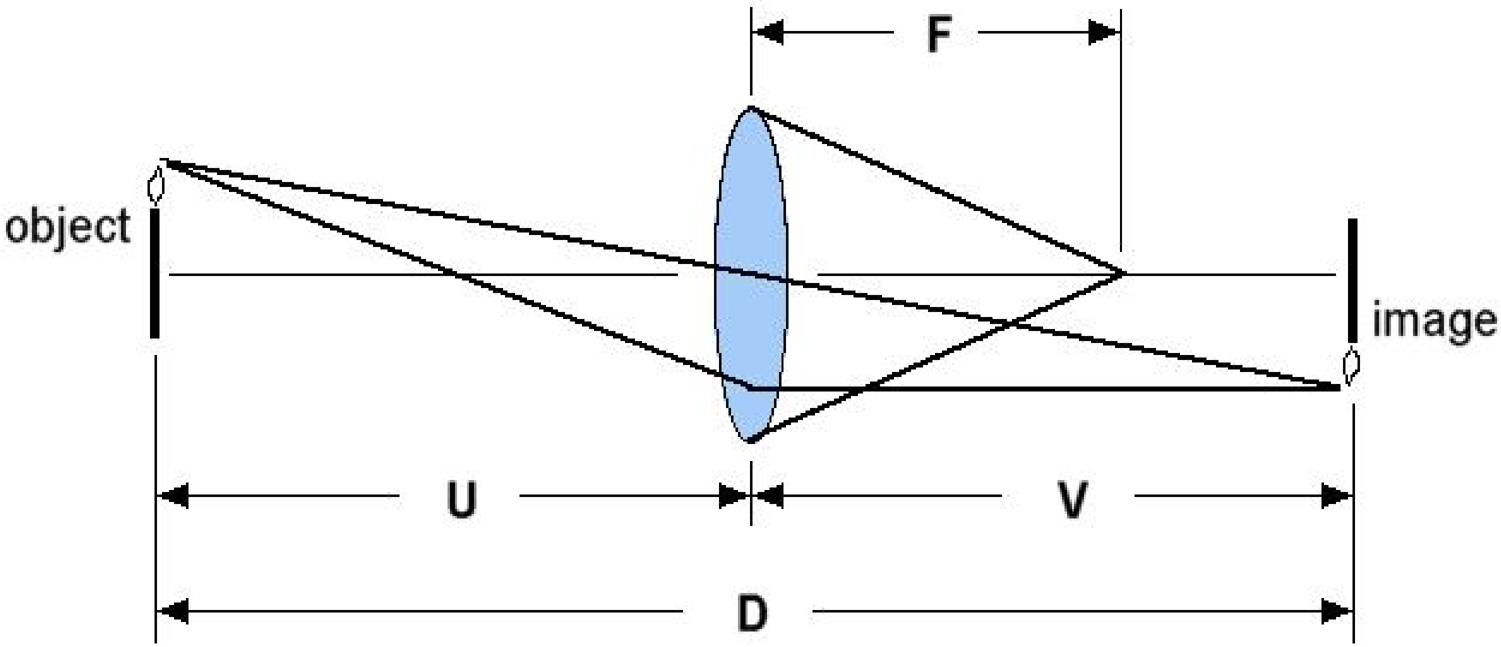
$\beta = I/(\pi r \alpha)^2$

Where r, it the radius and α is the half angle in radians

Electron Optics Basics - Brightness

- If the beam energy is constant, brightness is conserved or reduced by apperatures
- This is a consequence of classical statistical mechanics where the volume of momentum position "phase space" is conserved (Liouville equation)
  - $dxdydzdp_xdp_ydp_z)_{start} = dxdydzdp_xdp_ydp_z)_{end}$

Electron Optics Basics – Lens Action



Geometrical Optics

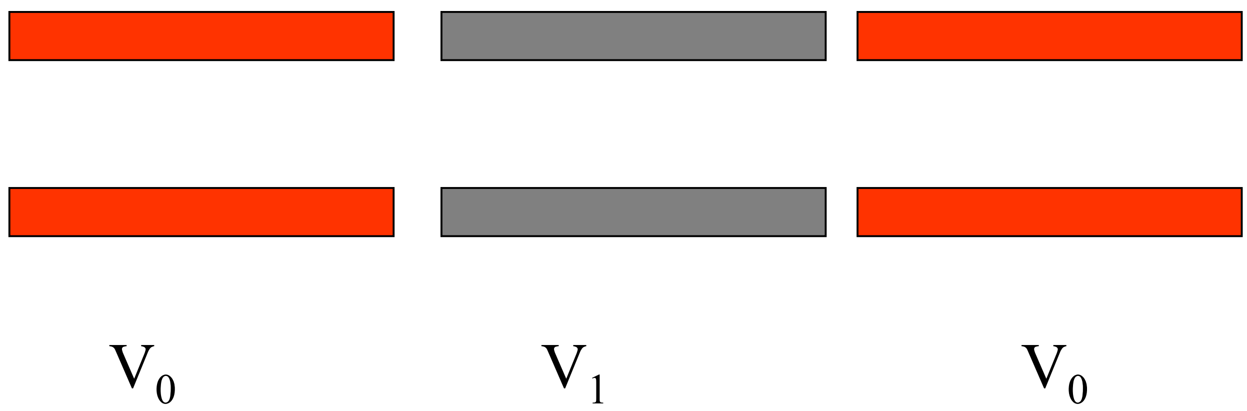
- Thin Lens assumption i.e. w<< u,v,f

$1/u + 1/v = 1/f$

$M = u/v$

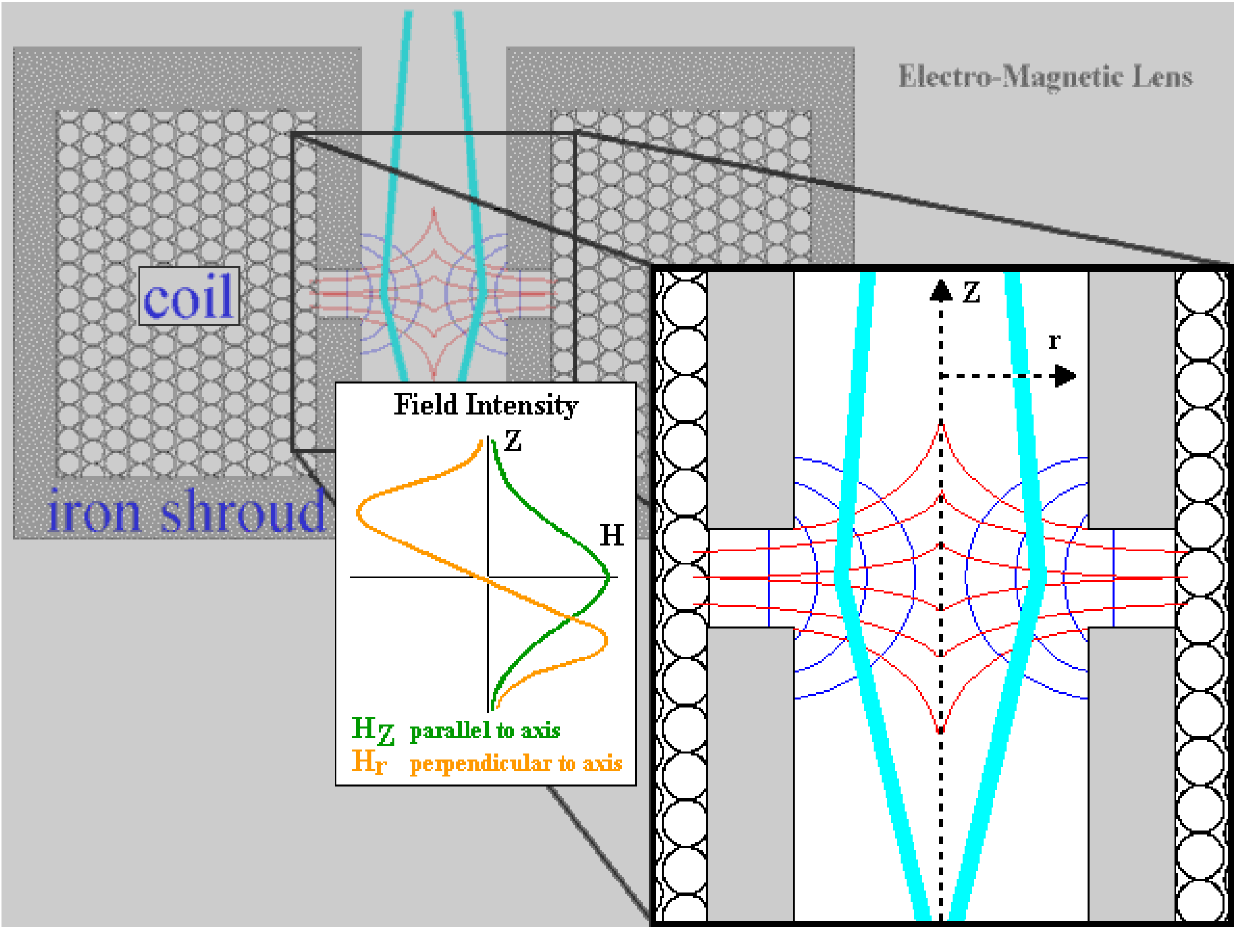
Electron Optics Basics – Electrostatic Lens

$F = q(E)$



Simion Demo

Electron Optics Basics – Magnetic Lens



$f = KV/(NI)^2$

Electron Optics Basics – Paraxial Equations for Magnetic Lens

- $\mathbf{F = q(E+v*B)}$
- $F_r = -ev_\theta B_z(z)$
- $F_r = -(e^2/(4m))B^2$
- $F = ma$
- $d^2r/dt^2 + (e^2/(4m)) B^2 r = 0$
- $(1/2) m v_z^2 = eV$
- $d^2r/dz^2 = -(e/(8m)) B^2 r/v_r$

Electron Optics Basics – Magnetic Lens

F = q(E+v*B) (the Lorentz force)

where F is the force,

q is the charge on the particle,

E is the electric field,

v the particle's velocity and

B is the magnetic field.

Electron Optics Basics – Aberrations

$d_{sa} = Cs\ \alpha^{3}/2$

where Cs = spherical aberration coefficient,

and a = semi angular aperture of the lens.

$d_{di} = 0.61\lambda/NA = 0.61\lambda/\ \alpha$ ($\lambda = 0.0037$ nm for 100kV)

$d_{ca} = C_c\,\alpha\,(\Delta V/V)$

α = half (semi) angle

Electron Optics Basics – Estimating Current and Spot size

- Lens Aberrations

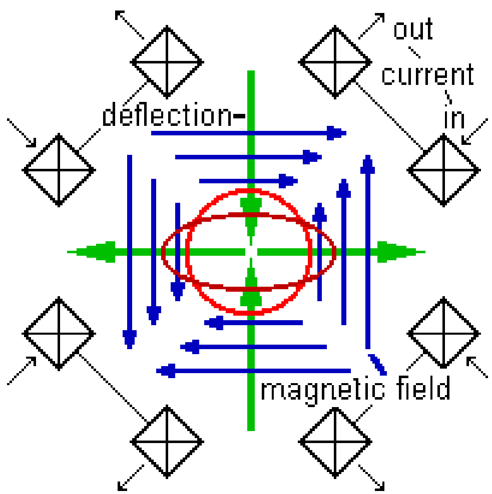
- $\Delta V/V$

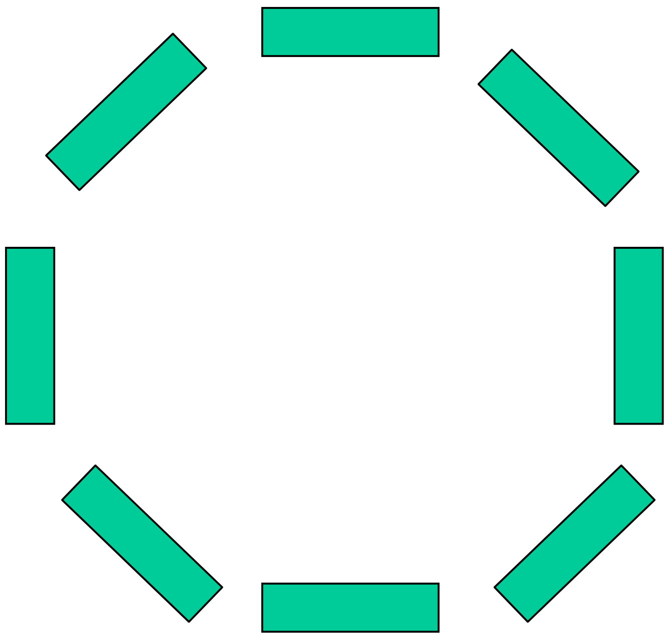
- Brightness

- Estimate using a sum in quadrature

$$D_t^2 = (\text{source}/M)^2 + (d_{sa})^2 + (d_{di})^2 + (d_{ca})^2$$

Electron Optics Basics – Stigmator / Deflector





Electron Optics Basics – Static Field Equations

Description of equation	Electric fields	Magnetic fields
Force	$\mathbf{F} = Q\mathbf{E}$	$d\mathbf{F} = (\mathbf{I} \times \mathbf{B})\, dl$ $\mathbf{F} = Q_m \mathbf{B}$
Basic relations for lamellar and solenoidal fields	$\nabla \times \mathbf{E}_c = 0\dagger$	$\nabla \cdot \mathbf{B} = 0$
Derivation from scalar or vector potential	$\mathbf{E}_c = -\nabla V$ $V = \frac{1}{4\pi\epsilon_0}\int_v \frac{\rho}{r}\, dv$	$\mathbf{B} = \nabla \times \mathbf{A}$ $\mathbf{A} = \frac{\mu_0}{4\pi}\int_v \frac{\mathbf{J}}{r}\, dv$
Constitutive relations	$\mathbf{D} = \epsilon\mathbf{E}$	$\mathbf{B} = \mu\mathbf{H}$
Source of electric and magnetic fields	$\nabla \cdot \mathbf{D} = \rho$	$\nabla \times \mathbf{H} = \mathbf{J}$
Energy density	$w_e = \frac{1}{2}\epsilon E^2 = \frac{1}{2}ED$	$w_m = \frac{1}{2}\mu H^2 = \frac{1}{2}BH$
Capacitance and inductance	$C = \frac{Q}{V}$	$L = \frac{\Lambda}{I}$
Capacitance and inductance per unit length of a cell	$\frac{C}{d} = \epsilon$	$\frac{L}{d} = \mu$
Closed path of integration	$\oint \mathbf{E} \cdot d\mathbf{l} = \mathcal{V}$ $\oint \mathbf{E}_c \cdot d\mathbf{l} = 0$	$\oint \mathbf{H} \cdot d\mathbf{l} = F = NI$ $\oint \mathbf{H} \cdot d\mathbf{l} = 0$ no current enclosed
Derivation from scalar potentials	$\mathbf{E}_c = -\nabla V$	$\mathbf{H} = -\nabla U$ in current-free region

† $\mathbf{E}_c$ is the static electric field intensity (due to charges). $\mathbf{E}$ (without subscript) implies that emf-producing fields (not due to charges) may also be present.

Electron Optics Basics – Lens Field Equations

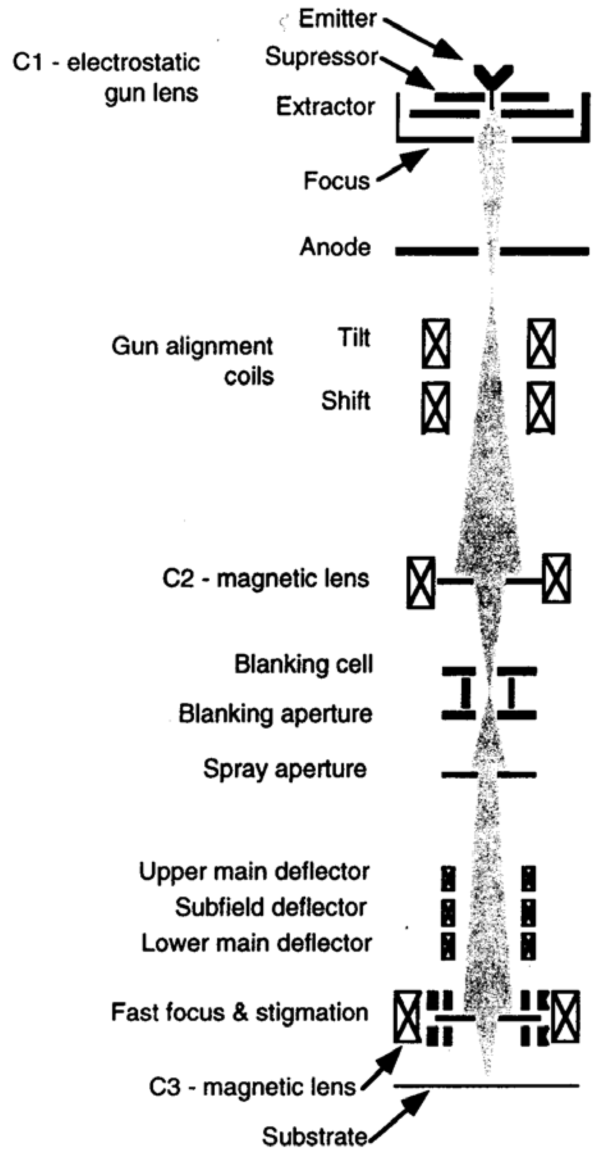
- Electrostatic – charge free Laplace equation
  - $\nabla^2\Phi = -\rho/\varepsilon = 0$
  - $E = - \nabla \Phi$
- Magnetic Potential
  - $\nabla x\ A = B$
  - $\nabla^2 A = - \mu J$
  - $H = - \nabla U$

Electron Optics Basics – Solutions

Procedure to solve Electron Optics Problems

- Define the geometry of the lens
- Solve the Laplace equation Using finite element or difference methods, i.e. solve a very large but sparce matrix
- Integrate the trajectories
- Plot and summarize the results
- Demo next week!

Electron Optical Layout for the Leica VB6



Project Guidelines I

- A project is required for the class and is expected to be a substantial part of the learning experience. The scope of the project should be realistic and take into account the limitations in time and materials. The project should explore a scientific application where electron beam lithography is need to achieve a result, or the electron beam lithographic process itself. The project will consist of a written proposal, which must describe the planned experiments together with a suitable schedule. The proposals will be reviewed to make sure that the scope is appropriate. The project milestones are expected to be followed. A written report of the project results and a formal presentation to the class are required.
- Proposals due Tuesday, February 18th
- The report is due Tuesday, May 6th
  - The report should be formatted in the style of a JVST paper, 4-6 pages in length. Each journal page is approx. 900 words, and each figure is equivalent to 200 words
- Class presentations will be on May 13th, which will be the last day of class. Each presentation will be 15 minutes long in the style of a conference talk.
  - Allow 1 minute per viewgraph

Project Guidelines II

- The work at LBL will be under the supervision of E.H. Anderson, J.A. Liddle or Weilun Chao
- The project can be related to the thesis work of the student, but should not be in the critical path!
- The project should use readily available materials and processes to the fullest extent possible. Health and safety issues may restrict materials and processes – investigate these possibilities early
- Samples for e-beam lithography can be on 3 – 8" wafers and quartz plates. No fragments!
- Data sets can be generated at LBL or with any CAD system that produces a suitable GDSII file
- Start prototyping and process development early!

Project Hints

- The voice of experience….
  - How hard could it be….?
  - What could possibly go wrong….?
- Keep the project scope simple, focused and reasonable. Estimate what you think you can do, and divide by two, focusing on the critical elements. This is a class project and not a thesis!
- Start early! Experimental efforts always take longer than expected, even when you know that experimental efforts always take longer than expected (yes, this is recursive!). Lots of things can go wrong in the lab, and often do. Remember, if you can't imagine how something could fail, it just shows a lack of imagination!
- Don't reinvent the wheel – if someone has already gone to the trouble of developing a process, use it!
- The written proposal is only a plan and *"no plan survives contact with the enemy"*. Be prepared to update your plan in light of experience.

Project Proposals Due Next Tuesday!!

The Plan

Task1 xxxxxxxxxxxxx

Task2 xxxxxxxxxxxxx

Task3 xxxxxxxxxxxx

Task4 xxxxxX

Report xxxxxxxxxX

Presentation xxxX

Project Proposals Due Next Tuesday!!

What really happens

Task1	xxxxxxxxxxxx (procrastinate)
Task2	xxxxxxxxxxxx (problems)
Task3	xxxxxxxxxxx (equipment down)
Task4	xxxxxX (luck)
Panic	xxxxxxxxxxxxxxxxx
Report	xX
Presentation	xxxX